

Design of modular wireless sensor

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The paper addresses combinatorial approach to design of modular wireless sensor as composition of the sensor element from its component alternatives and aggregation of the obtained solutions into a resultant aggregated solution. A hierarchical model is used for the wireless sensor element. The solving process consists of three stages: (i) multicriteria ranking of design alternatives for system components/parts, (ii) composing the selected design alternatives into composite solution(s) while taking into account ordinal quality of the design alternatives above and their compatibility (this stage is based on Hierarchical Morphological Multicriteria Design - HMMD), and (iii) aggregation of the obtained composite solutions into a resultant aggregated solution(s). A numerical example describes the problem structuring and solving processes for modular alarm wireless sensor element.

Keywords: wireless sensor, modular design, configuration, combinatorial optimization, composition, synthesis, hierarchical design, morphological design, aggregation

1. Introduction

In recent years the significance of sensor systems/networks is increased (e.g., [1], [5], [6], [16], [22], [27]). In general, it may be reasonable to consider a simplified 3-layer architecture of a sensor system (Fig. 1): (i) sensors and sensor local networks (sensor subsystem layer), (ii) communication network (transportation layer), and (iii) management subsystem (control layer: information analysis and integration/fusion, decision making and control) (e.g., [6], [16], [27]).

In the article, a hierarchical modular design of configuration for wireless sensor element is examined. The problem corresponds to layer 1 of the three-layer sensor system structure above. A real world numerical example is targeted to a fire alarm wireless sensor element.

Note various approaches have been applied for the design of system configurations [9]: (1) the shortest path problem [2]; (2) evolutionary approaches (e.g., [17]); (3) multi-agent approaches (e.g., [3]); (4) approaches based on fuzzy sets (e.g., [21]); (5) composite constraint satisfaction

problems (e.g., [19], [24]);

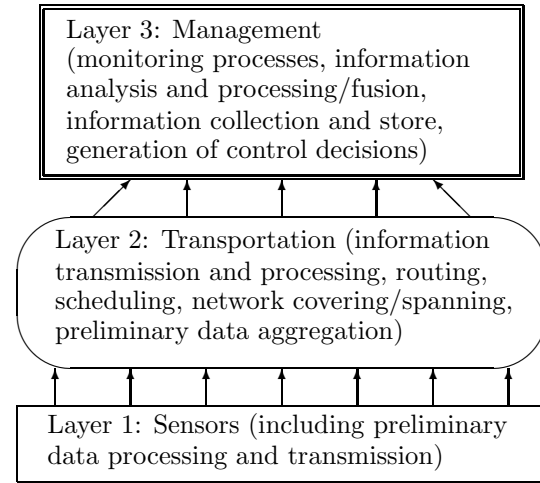


Fig. 1. Sensor system (three layers) [13]

(6) ontology-based approaches (e.g., [4]); (7) multicriteria multiple choice problem (e.g., [23]); (8) hierarchical multicriteria morphological design (HMMD) approach ([7], [8], [9]); (9) AI techniques (e.g., [14], [15], [25], [26]); and (10) design grammars approaches (e.g., multidisciplinary grammar approach that includes production rules and optimization, graph grammar approach) (e.g., [20]). A survey of combinatorial optimization approaches to system configuration

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design is presented in [9].

In this article, a generalized composite design framework for modular systems is used (Fig. 2): selection of design alternatives (DAs) for system components/parts, combinatorial synthesis (composition) of the composite solutions, and aggregation of the obtained solutions to get a resultant aggregated solution.

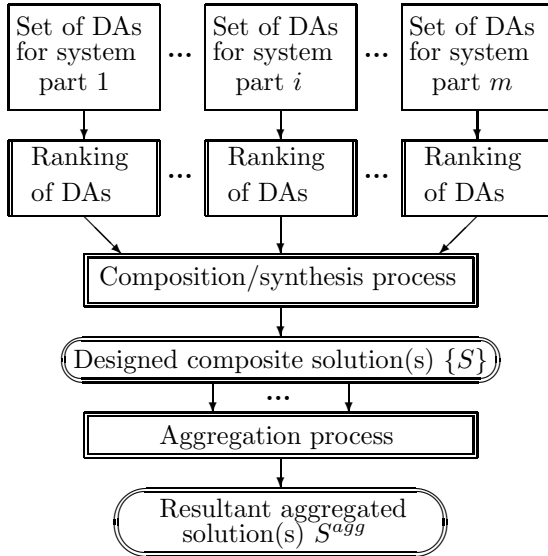


Fig. 2. Selection, composition, aggregation

The approach is based on three optimization problems:

I. Multicriteria ranking (outranking technique as a modification of ELECTRE method is used [18]).

II. Morphological synthesis based on morphological clique problem (as Hierarchical Morphological Multicriteria Design - HMMD) ([7], [8], [9], [12]).

III. Aggregation of the obtained composite solutions into the resultant aggregated solution(s) (aggregation strategies are used, e.g., design of system “kernel” and its extension) [11] (here knapsack-like problems are solved).

The illustrative numerical design example involves hierarchical structure of sensor (and-or tree model), design alternatives (DAs) for system parts/components, Bottom-Up solving process. Estimates of DAs and their compatibilities are based on expert judgment.

A preliminary material of the paper was published as conference paper [13].

2. Structure of Sensor and Estimates

The following simplified illustrative hierarchical structure of an alarm wireless sensor element is examined (Fig. 3):

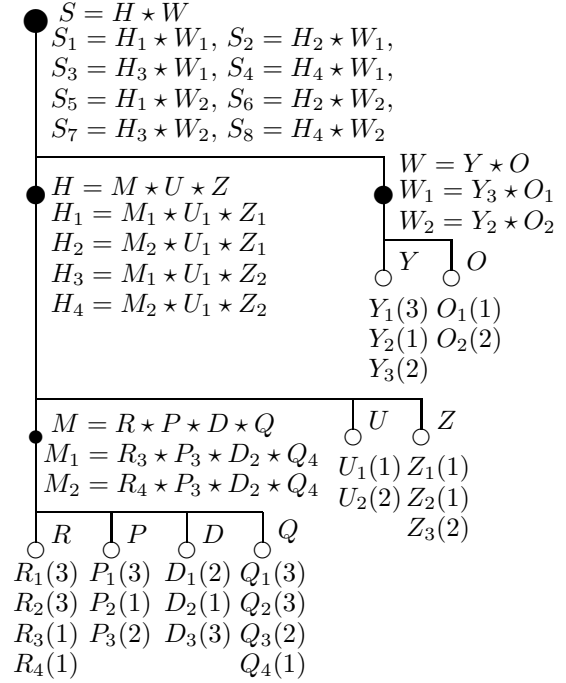


Fig. 3. Structure of wireless sensor element

0. Alarm wireless sensor element $S = H * W$.

1. Hardware $H = M * U * Z$.

1.1. Microelectronic components $M = R * P * D * Q$.

1.1.1. Radio R : Chipcon CC2420 Radio $R_1(3)$, Chipcon CC1000 Radio $R_2(4)$, Semtech XE1205 Radio $R_3(2)$, Infineon TDA5250 Radio $R_4(1)$.

1.1.2. Microprocessor P : Atmel ATmega128 with 10-bit ADC $P_1(3)$, Atmel AVR AT90S2313 $P_2(1)$, Texas Instruments MSP430F16 with 12-bit ADC/DAC $P_3(2)$.

1.1.3. DAC/ADC D : Atmel ATmega128L embedded 10-bit ADC $D_1(2)$, Texas Instruments MSP430F16 embedded 12-bit ADC/DAC $D_2(1)$, Analog Devices 14-bit AD679 $D_3(3)$.

1.1.4. Memory Q : No external memory $Q_1(4)$, 4 Kb EEPROM $Q_2(3)$, 128 Kb Flash $Q_3(2)$, 1 Mb Flash $Q_4(1)$.

1.2. Power supply U : 2800 mAh NiMh Battery $U_1(1)$, 1500 mAh Li-Ion Battery $U_2(2)$.

1.3. Sensor Z : Edwards 284b-pl Heat Detector $Z_1(1)$, 123 Security Systems Photoelectric 2-Wire Smoke $Z_2(2)$, Multisensing Fire Detector $Z_3(3)$.

2. Software $W = Y \star O$.

2.1. Sensor software Y : Zigbee/802.15.4 & Application $Y_1(3)$, TinyOS BMAC & Application $Y_2(1)$, Ad-Hoc software & Application $Y_3(2)$.

2.2. OS O : No OS, Simple run-time environment $O_1(1)$, TinyOS $O_2(2)$.

Table 1. Estimates of DAs upon criteria

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	Prio- rity
R_1	13	80	25	250				3
R_2	11	160	29	76				3
R_3	6	600	25	76				1
R_4	8	200	17	64				1
P_1	8		8	16				3
P_2	2.5		5	10				1
P_3	11		2	12				2
D_1	0		2	150	10			2
D_2	0		1	200	12			1
D_3	4		4	250	14			3
Q_1	0		0	0		0		3
Q_2	1		2	3		1024		3
Q_3	3		3	2		131072		2
Q_4	3		3	2		1048576		1
U_1	3					2800		1
U_2	10					1500		2
Z_1	10				2			1
Z_2	25				5			1
Z_3	50				16			3
Y_1	100					15000	5	3
Y_2	50					6000	6	1
Y_3	100					4000	11	2
O_1	0					2000	4	1
O_2	0					4500	0	2

The following generalized set of criteria for DAs is used (criteria weights are shown in parentheses, symbol – corresponds to the case when minimum value is the best one): cost C_1 (-100), radius C_2 (1), power consumption C_3 (-80),

speed/frequency C_4 (1), fidelity C_5 (10), capacity(memory) C_6 (0.5), and development duration C_7 (1000). Estimates of DAs upon the criteria are presented in Table 1 (expert judgment).

The resultant priorities of DAs are pointed out in Fig. 3 (priorities are shown in parentheses). and in Table 1 (a modification of outranking technique ELECTRE was used [18]).

Table 2 and Table 3 contain estimates of compatibility between DAs. Mainly, estimates are illustrative ones. For components of M , U and S equal compatibility estimates (between corresponding local DAs) are considered.

Table 2. Compatibility

	P_1	P_2	P_3	D_1	D_2	D_3	Q_1	Q_2	Q_3	Q_4
R_1	3	3	3	3	3	3	3	3	3	3
R_2	3	3	3	3	3	3	3	3	3	3
R_3	3	3	3	3	3	3	3	3	3	3
R_4	3	3	3	3	3	3	3	3	3	3
P_1				3	0	1	3	3	3	3
P_2				0	0	1	3	3	3	3
P_3				0	3	1	3	3	3	3
D_1							3	3	3	3
D_2							3	3	3	3
D_3							3	3	3	3

Table 3. Compatibility

	O_1	O_2
Y_1	1	2
Y_2	0	3
Y_3	3	2

3. Combinatorial Synthesis

Second, Hierarchical Morphological Multicriteria Design (HMMD) based on morphological clique problem is considered (e.g., [7], [8], [9], [12]). HMMD generalizes morphological analysis that was suggested by F. Zwicky [28]. Development stages of morphological analysis based design approaches are presented in [12].

A examined composite (modular, decomposable, composable) system consists of components and their interconnection or compatibility (IC). Basic assumptions of HMMD are the following:

(a) a tree-like structure of the system; (b) a composite estimate for system quality that integrates components (subsystems, parts) qualities and qualities of IC (compatibility) across subsystems; (c) monotonic criteria for the system and its components; (d) quality estimates of system components and IC are evaluated by coordinated ordinal scales. The designations are: (1) design alternatives (DAs) for nodes of the model; (2) priorities of DAs ($r = \overline{1, k}$; 1 corresponds to the best level of quality); (3) an ordinal compatibility estimate for each pair of DAs ($w = \overline{0, l}$; l corresponds to the best level of quality). Generally, the basic phases of HMMD are:

1. Design of the tree-like system model.
2. Generation of DAs for leaf nodes of the model.
3. Hierarchical selection and composing of DAs into composite DAs for the corresponding higher level of the system hierarchy.
4. Analysis and improvement of composite DAs (solution(s)).

Let S be a system consisting of m parts (components): $P(1), \dots, P(i), \dots, P(m)$. A set of design alternatives (DAs) is generated for each system part above. The problem is:

Find composite design alternative $S = S(1) \star \dots \star S(i) \star \dots \star S(m)$ (one representative design alternative $S(i)$ for each system component/part $P(i)$, $i = \overline{1, m}$) with non-zero IC estimates between the representative design alternatives.

A discrete space of the integrated system excellence is based on the following vector: $N(S) = (w(S); n(S))$, where $w(S)$ is the minimum of pairwise compatibility between DAs which correspond to different system components (i.e., $\forall P_{j_1}$ and P_{j_2} , $1 \leq j_1 \neq j_2 \leq m$) in S , $n(S) = (n_1, \dots, n_r, \dots, n_k)$, where n_r is the number of DAs of the r th quality in S ($\sum_{r=1}^k n_r = m$). As a result, we search for composite decisions which are nondominated by $N(S)$ (i.e., Pareto-efficient solutions). Fig. 4 depicts the lattice of system quality (by elements; $m = 3, k = 3$).

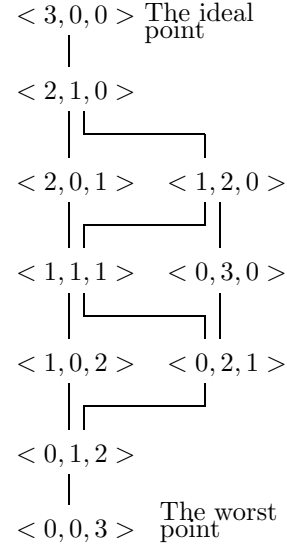


Fig. 4. Lattice of quality (by elements)

Now, let us consider combinatorial synthesis for the subsystems of wireless sensor. The obtained Pareto-efficient composite DAs for subsystems are the following:

- (a) $W_1 = Y_3 \star O_1$, $N(W_1) = (3; 1, 1, 0)$;
- (b) $W_2 = Y_2 \star O_2$, $N(W_2) = (3; 1, 1, 0)$;
- (c) $M_1 = R_3 \star P_3 \star D_2 \star Q_4$, $N(M_1) = (3; 3, 1, 0)$.
- (d) $M_2 = R_4 \star P_3 \star D_2 \star Q_4$, $N(M_1) = (3; 3, 1, 0)$.

Fig. 5 and Fig. 6 illustrate solutions for M_1 and M_2 .

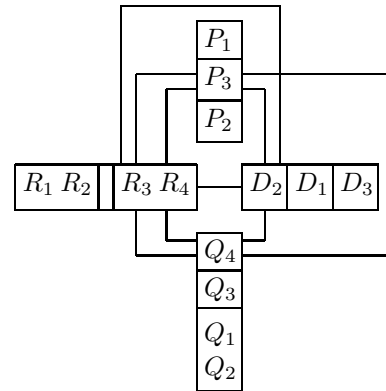


Fig. 5. Concentric presentation

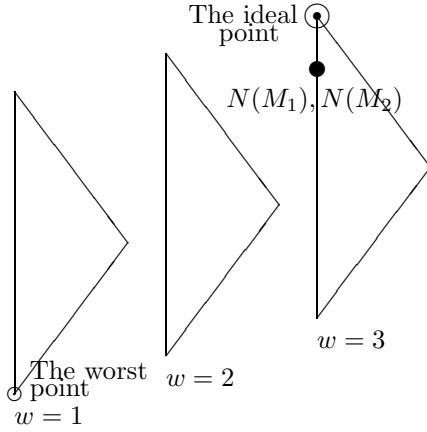


Fig. 6. Space of system quality

Further, the solutions for H are:

$$H_1 = M_1 \star U_1 \star Z_1 = (R_3 \star P_3 \star D_2 \star Q_4) \star (U_1 \star Z_1);$$

$$H_2 = M_2 \star U_1 \star Z_2 = (R_3 \star P_3 \star D_2 \star Q_4) \star (U_1 \star Z_2);$$

$$H_3 = M_1 \star U_1 \star Z_1 = (R_4 \star P_3 \star D_2 \star Q_4) \star (U_1 \star Z_1);$$

$$H_4 = M_1 \star U_1 \star Z_2 = (R_4 \star P_3 \star D_2 \star Q_4) \star (U_1 \star Z_2).$$

Finally, eight resultant solutions are obtained:

$$S_1 = H_1 \star W_1 = (M_1 \star U_1 \star Z_1) \star (Y_3 \star O_1) = ((R_3 \star P_3 \star D_2 \star Q_4) \star (U_1 \star Z_1)) \star (Y_3 \star O_1);$$

$$S_2 = H_2 \star W_1 = (M_2 \star U_1 \star Z_1) \star (Y_3 \star O_1) = ((R_4 \star P_3 \star D_2 \star Q_4) \star (U_1 \star Z_1)) \star (Y_3 \star O_1);$$

$$S_3 = H_3 \star W_1 = (M_1 \star U_1 \star Z_2) \star (Y_3 \star O_1) = ((R_3 \star P_3 \star D_2 \star Q_4) \star (U_1 \star Z_1)) \star (Y_3 \star O_1);$$

$$S_4 = H_4 \star W_1 = (M_2 \star U_1 \star Z_2) \star (Y_3 \star O_1) = ((R_4 \star P_3 \star D_2 \star Q_4) \star (U_1 \star Z_1)) \star (Y_3 \star O_1);$$

$$S_5 = H_1 \star W_2 = (M_1 \star U_1 \star Z_1) \star (Y_2 \star O_2) = ((R_3 \star P_3 \star D_2 \star Q_4) \star (U_1 \star Z_1)) \star (Y_2 \star O_2);$$

$$S_6 = H_2 \star W_2 = (M_2 \star U_1 \star Z_1) \star (Y_2 \star O_2) = ((R_4 \star P_3 \star D_2 \star Q_4) \star (U_1 \star Z_1)) \star (Y_2 \star O_2);$$

$$S_7 = H_3 \star W_2 = (M_1 \star U_1 \star Z_2) \star (Y_2 \star O_2) = ((R_3 \star P_3 \star D_2 \star Q_4) \star (U_1 \star Z_2)) \star (Y_2 \star O_2);$$

$$S_8 = H_4 \star W_2 = (M_2 \star U_1 \star Z_2) \star (Y_2 \star O_2) = ((R_4 \star P_3 \star D_2 \star Q_4) \star (U_1 \star Z_2)) \star (Y_2 \star O_2).$$

Note in the example the initial combinatorial set includes 5184 ($4 \times 3 \times 3 \times 4 \times 2 \times 3 \times 3 \times 2$) possible composite solutions.

4. Aggregation of Modular Solutions

Aggregation of composite systems (as modular solutions) can be considered as follows [11]. Fig. 7 illustrates substructure and superstructure for three initial solutions S^1 , S^2 , and S^3 .

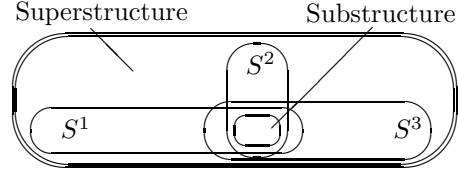


Fig. 7. Substructure and superstructure

In [11], basic aggregation strategies are described, for example:

1. Extension strategy: 1.1. building a “kernel” for initial solutions (i.e., substructure/subsolution or an extended subsolution), 1.2. generation of a set of additional solution elements, 1.3. selection of additional elements from the generated set while taking into account their “profit” and resource requirements (i.e., a total “profit” and total resource constraint(s)) (here knapsack-like problems are used).

2. Compression strategy: 2.1. building a supersolution (as a superstructure), 2.2. generation of a set of solution elements from the supersolution as candidates for deletion, 2.3. selection of the elements-candidates for deletion while taking into account their “profit” and resource requirements (i.e., a total profit and total resource constraint(s)) (here knapsack-like problems with minimization of objective function are used).

A general aggregation strategy has to be based on searching for a consensus/median solution S^M (“generalized” median) for the initial solutions $\bar{S} = \{S^1, \dots, S^n\}$ (e.g., [11]):

$$S^M = \arg \min_{X \in \bar{S}} \left(\sum_{i=1}^n \rho(X, S^i) \right),$$

where $\rho(X, Y)$ is a proximity (e.g., distance) between two solutions X and Y . Mainly, searching for the median for many structures is usually NP-complete problem. In our case, product structures correspond to a combination of tree, set of DAs, their estimates, matrices of compatibility estimates. As a result, the proximity between the structures are more complicated and the “generalized” median problem is very complex. As a result, simplified (approximate) solving strategies is often used, for example [11]: (a) searching for “set median” (i.e., one of the initial solutions

is selected), (b) “extension strategy” above, (c) “compression strategy” above.

In the example, eight obtained composite solutions are considered: $S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8$. The substructure of the eight solutions is presented in Fig. 8. This substructure is examined as system “kernel” for future extension. The superstructure is presented in Fig. 9.

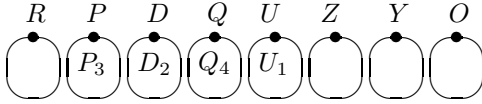


Fig. 8. Substructure (“kernel”)

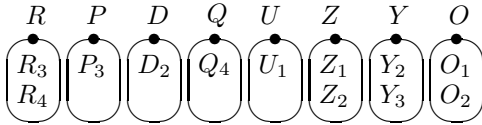


Fig. 9. Superstructure of solutions

The extension procedure based on multiple choice problem is the following. Table 4 contains design alternatives (DAs) and their estimates (ordinal scales, expert judgment). The design alternatives correspond to superstructure (Fig. 9).

Table 4. Design alternatives

κ	DAs	Binary variable	Cost a_{ij}	Profit c_{ij}
1	R_3	x_{11}	2	3
2	R_4	x_{12}	3	4
3	Z_1	x_{21}	4	3
4	Z_2	x_{22}	6	3
5	Y_2	x_{31}	7	3
6	Y_3	x_{32}	8	2
7	O_1	x_{41}	1	3
8	O_2	x_{42}	1	2

It is assumed design alternatives for different product components are compatible. The multiple choice problem is:

$$\max \sum_{i=1}^4 \sum_{j=1}^{q_i} c_{ij} x_{ij} \quad s.t. \quad \sum_{i=1}^4 \sum_{j=1}^{q_i} a_{ij} x_{ij} \leq b,$$

$$\sum_{j=1}^{q_i} x_{ij} = 1 \quad \forall i = \overline{1, 4}, \quad x_{ij} \in \{0, 1\}.$$

Clearly, $q_1 = 2, q_2 = 2, q_3 = 2, q_4 = 2$. The resultant aggregated solutions are (a simple greedy algorithm was used; the algorithm is based on ordering of elements by c_i/a_i):

- (1) $b^1 = 14$: $(x_{11} = 1, x_{21} = 1, x_{31} = 1, x_{41} = 1)$, $S_{b^1}^{agg} = R_3 \star P_3 \star D_2 \star Q_4 \star U_1 \star Z_1 \star Y_2 \star O_1$;
- (2) $b^2 = 15$: $(x_{12} = 1, x_{21} = 1, x_{31} = 1, x_{41} = 1)$, $S_{b^2}^{agg} = R_4 \star P_3 \star D_2 \star Q_4 \star U_1 \star Z_1 \star Y_2 \star O_1$.

5. Conclusion

In the article, hierarchical combinatorial approach to configuration of modular wireless sensor has been described. The solving framework is based on hierarchical model of the sensor element, morphological design method for combinatorial synthesis (building a special morphological clique), and aggregation of the obtained modular solutions (multiple choice problem). The suggested approach can be used for many modular systems. In the future it may be prospective to consider the following research directions: 1. taking into account uncertainty; 2. analysis of dynamical design problems; 3. usage of AI solving techniques' and 4. usage of the described application and solving approach in engineering/CS education.

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